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A Characteristic Scale on the Cosmic Microwave Sky

Elena Pierpaoli[1,2], Douglas Scott[1] & Martin White[3]

[1]Department of Physics and Astronomy, University of British Columbia, B.C. V6T 1Z1, Canada
[2]Canadian Institute for Theoretical Astrophysics,Toronto, ON M5S 3H8, Canada
[3]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, U.S.A.

The 1965 discovery (1) of the Cosmic Microwave Background (CMB) was key evidence supporting the hot Big Bang model for the evolution of the Universe. The tiny temperature variations discovered in 1992 (2) – of just the right size for gravity to have grown the observed large-scale structures over the age of the Universe – established gravitational instability as the mechanism of structure formation. Those first measurements of CMB anisotropy on tens of degree scales have been followed by many experiments concentrating on smaller angular scales. Even 5 years ago (3) there were indications for enhanced temperature variations on half-degree scales. By combining results from all current experiments it is now clear that this 'excess power' decreases again below half a degree – in other words there is a distinctive scale imprinted upon the microwave sky. The existence of such a feature at roughly $0\overset{\circ}{.}5$ has profound implications for the origin of structure in the Universe and the global curvature of space.

It is conventional to expand the CMB sky into a set of orthogonal basis functions labeled by 'multipole number' ℓ. Functions with higher ℓ probe smaller angular scales. We then consider the squares of the expansion coefficient amplitudes as a function of ℓ, or inverse angle, and this is referred to as the 'anisotropy power spectrum' (4). This power spectrum is easy to compute theoretically, and in popular models contains essentially all of the cosmological information in the CMB.

What remains is to obtain this power spectrum experimentally. Each experiment is sensitive to a range of angular scales, and its sensitivity as a function of ℓ is encoded in its 'window function'. Several experiments can now divide their ℓ range into overlapping window functions and thus obtain information on the shape of the power spectrum. Each experiment thus quotes results for one or more 'band-powers', which is the amplitude of the anisotropies integrated over the window function (5). Individual experiments until now have had limited angular range, so each has provided only a small piece of the puzzle. However a number of different CMB experiments can be combined together to provide an essentially model-independent estimate of the power spectrum. This estimate, provided it is carefully calculated, can then be used to constrain models.

We used a maximum likelihood technique to combine the band-powers into a binned power spectrum encapsulating the knowledge gained from the different observations. We have included all the experimental results of which we are currently aware. Specifically those collected in Ref. (6), together with the more recent results of the QMAP (7), MAT (8), Viper (9) and BOOM97 (10) experiments; as summarized in the RADPACK package (11) with some minor corrections.

For definiteness we have divided the range $\ell = 2$–1000 into 8 bins (spaced at roughly equal logarithmic intervals, with slight adjustment to allow for regions where data are scarcer). As the experimental situation improves, particularly at higher ℓ, we expect that emphasis will shift to plots linear in ℓ and having a wider range – however, for now the situation is adequately summarized in a log plot. We have approximated the power spectrum as a piece-wise constant and fit the values of that constant within each bin to the combined data, taking into account non-symmetric error bars and calibration uncertainties in a manner similar to (12). We maximize the likelihood function for the 8 parameters (plus 17 calibrations) using a simulated annealing technique (13). From the maximum likelihood position we then use Monte-Carlo integration to calculate the covariance matrix of the parameters. The final result is a power spectrum, with realistic estimates of the error bars and bin-to-bin correlations. We show the points and errors in Figure 1, and present the values in Table 1.

$\ell_{\rm min}$	$\ell_{\rm max}$	$\ell(\ell+1)C_\ell/2\pi$ (μK^2)	$\pm 1\sigma$ (μK^2)
2	7	639	152
8	15	814	160
16	49	1048	298
50	99	1394	367
100	149	3084	597
150	249	6548	590
250	449	2678	551
450	999	1971	825

Table 1: Band-powers and error bars plotted in Figure 1.

These points are somewhat correlated, with the strongest correlation being typically a 30% anti-correlation with immediately neighbouring bins, and more distant correlations being almost negligible. Table 2 explicitly shows the correlations between the difference bins, fixing the calibrations at the maximum likelihood value. Any use of these binned poewr spectrum estimates to constrain cosmological models should include these correlations. Our best fitting model has $-2\ln\mathcal{L} = 78$, a marginally acceptable fit. We note that if the experimental calibrations were not allowed to float, then the overall χ^2 would be far from acceptable. In fact we find that the best fitting calibration scalings are very close to unity for most experiments, with the most discrepant values being 0.76 for MAT97, 0.83 for QMAT, 1.15 for MSAM and 1.11 for BOOM97.

Bins	2–7	8–15	16–49	50–99	100–149	150–249	250–449	450–999
2–7	1.00	—	—	—	—	—	—	—
8–15	-0.02	1.00	—	—	—	—	—	—
16–49	-0.04	-0.08	1.00	—	—	—	—	—
50–99	0.02	0.03	-0.33	1.00	—	—	—	—
100–149	0.01	-0.01	0.05	-0.42	1.00	—	—	—
150–249	-0.00	0.00	-0.04	0.07	-0.41	1.00	—	—
250–449	0.01	-0.01	0.01	-0.01	0.04	-0.22	1.00	—
450–999	0.06	0.08	0.01	0.02	0.01	0.05	-0.26	1.00

Table 2: Correlations between the 8 bins shown in Figure 1.

These data show a prominent, localized peak in the angular power spectrum. There is a distinct fall-off at high ℓ, which is indicated within the data sets of individual experiments (particularly Saskatoon (14), MAT, Viper and BOOM97), but is more dramatically revealed in this compilation of data sensitive to different angular scales. Further confidence in the decrease in power comes from upper limits at even larger ℓ, not plotted or used in our fit.

In other words, there is a particular angular scale on which CMB temperature fluctuations are highly correlated and that scale is around $\ell = 200$, or $0^\circ\!.5$. It corresponds theoretically to the distance a sound wave can have traveled in the age of the Universe when the CMB anisotropies formed. Such a characteristic scale was suggested in models of cosmological structure formation at least as far back as 1970 (15).

The field is now in an exciting phase, with two main parts: (a) confirming/refuting the basic paradigm; and (b) constraining the parameters within that paradigm. These go hand in hand, of course. The peak prominent in Figure 1 confirms our ideas of the early evolution of structure. Understanding the physical basis for the peak allows a constraint to be placed on the curvature of the universe (e.g. 16, 17). The overall geometry of space appears to be close to flat, indicating that something other than normal matter contributes to the energy density of the Universe. Together with data from distant supernovae and other cosmological tests, this implies that models with cold dark matter and Einstein's cosmological constant are in good shape (18).

Soon the detailed structure of the CMB spectrum should be measurable and we expect it will contain a series of peaks and troughs. Finding such structure in the spectrum at the correct ℓs would be strong confirmation for 'adiabatic' fluctuations (which perturb matter and radiation in a similar way) produced at very early times. Eventually this would lead to the possibility of 'proving' inflation, or stimulating research on other ways of generating similar fluctuations on apparently acausal scales. Of course, failure to see multiple peaks in the predicted locations would require theorists to be more imaginative!

If we verify the framework we then need to determine precisely the parameters within our model; namely the amounts of matter of different types, the expansion rate, the precise form of the initial conditions, etc. With a well characterized set of initial conditions we will clearly wish to extend our understanding of cosmic origins to more recent epochs. Even here the upcoming high resolution maps of the CMB will play a crucial role carrying imprints, through reionization and gravitational lensing, of object formation in the recent universe.

The future remains bright. New results from a long duration flight of the BOOMERANG experiment are expected in the very near future. There are also several ground-based experiments, including interferometric instruments, nearing completion. NASA's Microwave Anisotropy Probe is expected to return data in 2001, and the ambitious Planck satellite is scheduled for launch in 2007. Beyond this, information from challenging CMB polarization measurements and the combination of CMB data with other cosmological probes will be even more powerful.

We are on the threshold of precision measurements of the global properties of our Universe. The history of CMB research can be split into 5 phases. Firstly, its mere existence showed that the early Universe was hot and dense. Secondly, the blackbody nature of the CMB spectrum and its isotropic distribution imply that the Universe is approximately homogeneous on large scales. The third step came with the detection of anisotropies which confirmed the theory of structure formation through gravitational instability. Here we have outlined a fourth stage, which is the discovery of a characteristic (angular) scale on the CMB sky. This supports a model with adiabatic initial conditions and a Universe with approximately flat geometry. Higher fidelity data, of the sort which will soon be available, should decide whether or not our models are vindicated. And now we are on the verge of the fifth phase, which involves determining the precise values of the fundamental cosmological parameters to figure out exactly what kind of Universe we live in.

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Authors e-mail addresses: elena@astro.ubc.ca; dscott@astro.ubc.ca; mwhite@cfa.harvard.edu

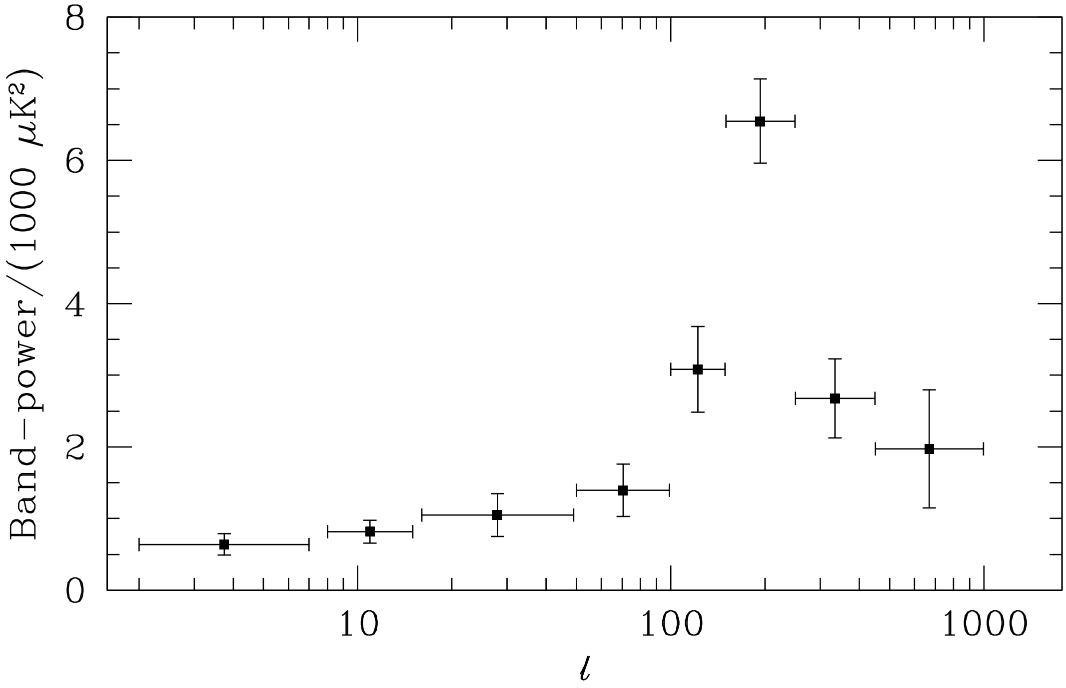

Fig. 1.— The power spectrum of Cosmic Microwave Background anisotropies. This is a plot of temperature variations versus multipole, which is the equivalent of an inverse angle. The plot is a binned spectrum from all the currently available data. There is clearly a peak which is localized in angle.